

An Analysis of the Lumber Planing Process: Part I¹

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Report of study of the peripheral-milling process of planing lumber. Relationships were determined between cutterhead horsepower and various combinations of specimen, cutterhead, and feed factors. Power demand curves are interpreted by comparison with simultaneous one micro-second photos of chips. Secondary consideration is given to quality of surface obtained. The cutterhead variables, feeds, and speeds are in range of those commonly used in industry.

Introduction

THIS INVESTIGATION WAS CONDUCTED to provide factual and fundamental information pertaining to the process of planing lumber. In this discussion, the term "lumber planing process" is confined to peripheral milling only, as differentiated from planing by means of a fixed knife such as in a carpenter's plane.

Planing as here considered is the process of removing excess wood from lumber in the form of single chips. These single chips are formed by the intermittent engagement with the workpiece of the one to several knives carried on the periphery of a disk-shaped mount known as a cutterhead. The finished surface therefore consists of a series of individual knife traces, generated by the successive engagement of each knife.

It is apparent that there are two possibilities of workpiece-feed direction in relation to the direction of cutterhead rotation. In conventional or up-milling, the engaged knives of the cutterhead move counter to the movement of the workpiece. In down-milling the engaged knives move in

the same direction as the workpiece. This portion of the work is concerned with the up-milling process.

The study was designed to determine the relationship between cutterhead-horsepower requirement and various combinations of specimen, cutterhead, and feed factors. The cutterhead variables as well as the feeds and speeds employed are in the range of those commonly encountered in industry.

Before discussing the investigation, it is necessary to define the terms used. As the machining terminology used in metal working is widely accepted and is equally applicable to wood-working, such terminology as is appropriate is utilized. The conventional up-milling process is diagrammed with essential parts and dimensions labeled in Fig. 1.

Kinematics of Process

Although the path taken by the knife tip while in the process of chip

severance is frequently assumed to be circular, it is in fact cycloidal, or more broadly, trochoidal. The kinematics of this motion was recognized as early as 1900 (15)², and possibly earlier.

The curve defined by each knife tip is illustrated in Fig. 2. It will be noted that the curve is generated by considering the stock as fixed in space, and

² Numbers in parentheses refer to Literature Cited.

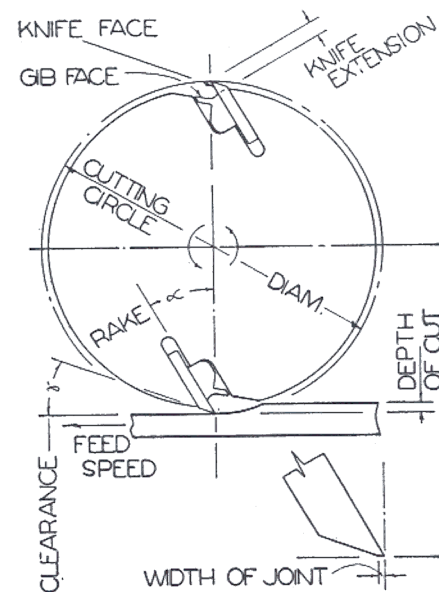


Fig. 1.—Terminology.

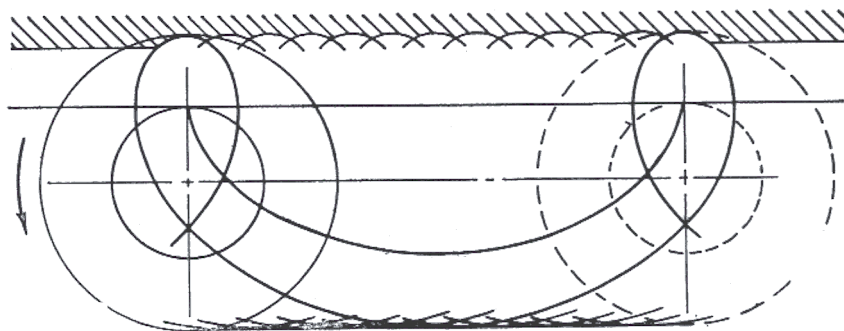


Fig. 2.—Curtate trochoid.

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allowing the cutterhead to rotate about a roll circle of suitable diameter to give a relative translatory velocity equal to the desired feed speed of the stock. The lower generated surface is the result of conventional or up-milling, whereas the top surface is accomplished by down-milling.

This concept has been visualized through the employment of a rack and pinion, as shown in Fig. 3. The geometry and kinematics of both up-milling (11) and down-milling (12) have been thoroughly explored by Martellotti, and will not be further discussed here.

Testing Technique

The test apparatus consisted of a slightly modified combination knife grinder and jointer. The lumber specimens, which ranged up to 20 feet long, were securely fastened to a strip of cold-rolled steel. This, in combination with a gravity actuated hold-down, provided the necessary specimen stability for the tests. The hold-down, and a specimen in running position, are illustrated in Fig. 4, the backing strip being connected by a roller chain to the output sprocket of a 1/2-HP variable speed gearmotor (out of the picture to the left).

With this arrangement feed speeds up to 600 FPM could be accomplished. This apparatus was particularly well suited for the purpose at hand, inasmuch as grinding of the knives could be accomplished on the machine. More important, the cutterheads could be jointed without being removed from the cutting spindle (Fig. 5).

To measure the input energy to the cutterhead motor, an Esterline Angus Graphic Watt Meter was selected in order that fluctuating readings would leave a record that could subsequently be averaged. This meter is illustrated in Fig. 4.

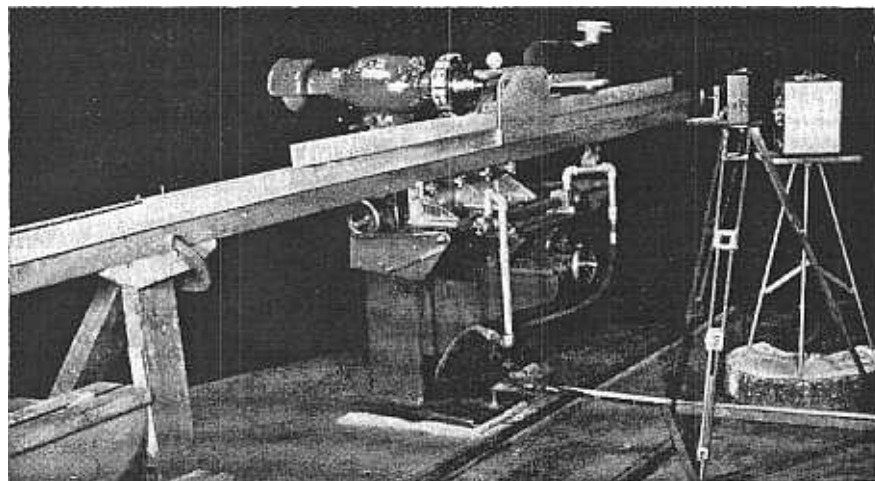


Fig. 4.—Apparatus for planing specimens up to 20 feet in length showing the workpiece secured to a steel strongback with traction chain running out of picture to left, extended bed with gravity holddown preceding cutterhead, dial indicator, shaving catcher, camera, light source, and recording watt meter.

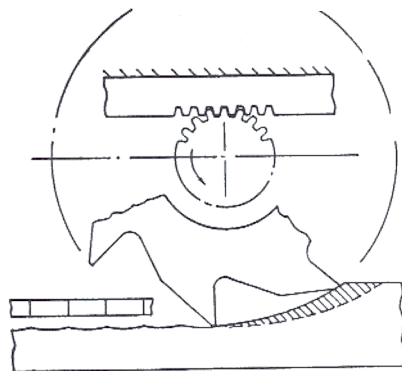


Fig. 3.—Path generated by up-milling cutter knife.

All of the experimentation was done at a nominal cutterhead RPM of 3600, that being the nominal RPM of the 3-horsepower, 220 volt, 3-phase, 60-cycle motor which was mounted directly on the cutterhead spindle. The actual horsepower and RPM output of the motor was established by means of a prony brake test made in conjunction with the recording watt meter.

The means of catching the shavings is illustrated in Fig. 4.

In order to photograph the transient phenomena of the chip formation, photographs were taken at night with the shutter on the camera open, the exposure being accomplished by the flashing of a General Electric one micro-second Photolight which illuminated the subject. This piece of apparatus contains a short-gap, high-pressure, inert-gas-filled tube with an energy storage capacitor, a high-voltage transformer, a rectifier, and a trigger circuit which releases the energy from the capacitor into the flash tube at the proper time. The arrangement of the camera and lighting apparatus is shown in Fig. 4.

The photographs taken by Patronsky (13) of a 4-inch diameter cutting-circle shaper head using an exposure

time of approximately 8 micro-seconds were instrumental in causing the present work, which at that time was in process, to be altered to the extent of seeking the faster exposure time of one micro-second in order to stop the motion of the 9-inch to 9 3/8-inch diameter heads employed. Notice was also taken of the high-speed motion picture study made by Hoyle and Cote (6).

The depth of cut was established by means of the dial indicator illustrated in Fig. 4. Specimen thickness was established by averaging readings taken with a screw type, 1-inch capacity micrometer. Specimen moisture content was determined through the procedure of oven drying representative portions of each specimen. Specific gravities were calculated for each specimen on an oven-dry weight and oven-dry volume basis, and where considered important, also on an oven-dry weight and green-volume basis.

To determine whether the moisture gradient changed abruptly at any point in each specimen, periodic checks were made with an electric moisture meter as the testing proceeded. The specimens which were to be tested dry were conditioned in the laboratory, where they reached equilibrium at 8 to 10 per cent moisture content, as recorded in the various data sections. Specimens which were to be tested in a water-saturated condition were pressure-treated in water at approximately 65 psi for periods ranging from three to eight days. A fire hose served as the pressure treating vessel.

The average loaded input wattage readings as recorded on the graphic watt meter were translated into gross output horsepower directly from the efficiency curve established by the prony brake calibration of the spindle-mounted motor. By subtracting from this figure the tare horsepower consumption represented by windage loss, which varied for each cutterhead condition, a net output horsepower was calculated. This represented the energy actually utilized in removing stock in the form of a plurality of single chips from the specimen under consideration.

Inasmuch as the width of the specimen face presented to the cutterhead varied somewhat with the individual specimen, the net horsepower figures were converted to indicate horsepower



Fig. 5.—Test set up illustrating spindle assembly rotated into position for jointing of cutterhead at 3600 RPM.

required per inch of stock width. This conversion was made on the assumption that the net horsepower requirement is a straight line function of stock width. This assumption is supported by investigators in the United States (14), and also by workers Beck (1) and Bobbe (2) (as reported by Kollmann). Each tabulated net horsepower value in the individual test data sections is the result of a single unreplicated observation.

The feed speed of the specimen corresponding to each set of conditions and each power reading was calculated by utilizing the relationship

$$F = Tn/G$$

where

F = feed rate in FPM

T = number of knives

n = cutterhead RPM at the load in question

G = knife marks per foot

The value of n was taken from the motor performance curve. The value of G was obtained by averaging measured values taken at third points on each specimen, and of course the number of knives was available for each test.

Experimental Section

Preliminary

A. Specimen Selection: The raw material used in the tests was Douglas-fir heartwood. Each test was designed around matched specimens as described in the individual test data tabulation. No effort was made to match specimens between tests, but rather within individual tests. In all cases the material was selected for its uniformity of structure and freedom from knots or areas of diagonal grain.

To facilitate selection of specimens, they were all obtained in a dry, surfaced condition from retail lumber yards in Seattle, Wash. In general, the raw material at the time of purchase was at approximately 10 per cent moisture content and the width of face to be machined was approximately $\frac{3}{4}$ inch. All machining was accomplished with the feed direction aligned with the longitudinal axis of the specimen.

B. Knives and Cutterheads: The two cutterheads had cutting-circle diameters of approximately 9 and $9\frac{3}{8}$ inches. The 9-inch cutting-circle head was slotted to receive eight knives. The $9\frac{3}{8}$ -inch cutting-circle head was slotted to receive 12 knives.

Both cutterheads employed high-chrome, high-carbon, $\frac{5}{16}$ -inch thick corrugated-back straight knives. All knives had approximately the same hardness, being in the range of 50 to 61 Rockwell C. In all cases the knives were freshly jointed before test, the width of joint being indicated

Table 1.—RESUME OF FACTORS APPLYING TO TEST BAKER

Variable Factors:

Cutterhead Types

- #2 $2\frac{1}{4}$ inch high 8-knife jointer body fitted with $\frac{5}{16}$ inch thick corrugated-back knives ground to an 8.99 inch diameter cutting-circle with 0.022-inch width of joint, 0.295-inch knife extension beyond gib, 30-degree rake, 20 degree clearance and fitted with gibs having flat (i.e., not concave) chipbreaking surfaces at right angles to the knife face.
- #3 $2\frac{1}{4}$ inch high 8-knife jointer head body fitted with $\frac{5}{16}$ inch thick corrugated back knives ground to a 9.00-inch diameter cutting-circle, with 0.018-inch width of joint, 0.305-inch knife extension beyond gib, 30-degree rake, 20-degree clearance and fitted with concave-face gibs.

Per cent Moisture Content: Dry, i.e., 10.0 \pm 0.5

Green, i.e., 101 \pm 11

Grain Type: Flat, i.e., with annual rings making an angle of 4 \pm 4 degrees with the machined surface

Edge, i.e., with annual rings making an angle of 90 \pm 2 degrees with the machined surface

Depth of Cut in Inches: 1/32, 1/16, 3/32, and $\frac{1}{8}$

Fixed Factors:

Specimen:

General Description: A 20-foot long dry (10.6 percent M.C.) 2 by 6 was ripped in such a fashion that four pieces were obtained, two of which were flat-grain and two edge-grain. One edge-grain and one flat-grain piece were pressure treated in water at approximately 65 psi for four days to simulate green condition.

Species: *Pseudotsuga taxifolia*

Wood Type: Heart

Rings per inch: 25 \pm 4

Width of Machined Surface in Inches: 0.764 \pm 0.03

Spiral Grain: One inch per foot favoring feed

Specific Gravity:

Based on O.D. weight and green volume: 0.451 \pm 0.007

Based on O.D. weight and O.D. volume: 0.502 \pm 0.006

Inclination of Diagonal Grain to Direction of Feed: None

Cutterhead:

Number of Jointed Knives Cutting: 8

Cutting-Circle Diameter in Inches: 9.00

Width of Joint in Inches: Average for both cutterheads 0.020

Nominal RPM of Cutterhead: 3600

Feed Speed: 298 \pm 9 FPM

in the individual test data tabulations. Following jointing, each knife was honed on the face to remove any wire edge.

After each jointing and honing operation, but before any test readings were taken, a preliminary run was made of approximately 8 lineal feet of stock per knife, at a feed of 200 FPM and a depth of cut of 1/64 inch. The purpose of this preliminary dulling run was to eliminate the influence of the initial rapid deterioration of the cutting edge and yet leave the knife in a reasonably sharp condition.

The knife angles were dry ground on the test machine with a 7-inch diameter, dished, Norton 32 Alundum grinding wheel with 42 grit, K grade, 5 structure, and vitrified bond. In other words, a fairly coarse grit wheel of medium grade hardness with medium structure was used.

The knife angles were checked with a protractor within \pm 0.5 degree. No further dressing of the knife face was accomplished, except the light honing after jointing, as previously described. The jointing stone was Norton 38 Alundum with 80 grit, H grade, and vitrified bond—a medium grit stone on the soft side.

C. Surface Analysis: As related information of considerable interest, the surface quality resulting from the various combination of factors was recorded. The surface defects of raised grain, fuzzy grain, torn grain, and chip marks are recognized. Following each cut the resulting surface was graded on the degree of severity of each defect.

Raised grain is defined as a roughened condition of dressed lumber in which hard summer wood is raised

above the softer spring wood, but not torn loose from it. Fuzzy grain is characterized by fiber bundles that are not cut off cleanly, but which project above the line of cut so as to present a relatively woolly appearance.

Torn or chipped grain is caused by a breaking out of particles below the line of cut. Chip marks may be caused by shavings, or more frequently by minute fiber bundles which split over or otherwise adhere to the extreme knife tip. These chips, particles, or fiber bundles are carried around and indented into the finished surface of the lumber.

A rating scale of 0 to 5 was employed for each factor, a 0 rating signifying absence of the defect, and a 5 rating indicating extreme severity of defect. The rating was visual, and though open to some latitude of interpretation, a fairly good idea of the surface quality could be deduced from the rating figures. Other investigators (4) (5) have also used similar systems of evaluating planed lumber surfaces.

In the tabular presentation of the information in the individual test sections, the surfaces have been designated simply as satisfactory or unsatisfactory. A surface was considered satisfactory if it contained no defect rating over 1, except in the case of chip marks, where a defect rating of 2 was permitted.

This classification system takes no cognizance of the distance between knife marks, wave height, or radius of knife trace, which are strictly functions of the kinematics of the process. Of course, this rating scheme is completely arbitrary, as a surface quality satisfactory for one purpose may be

Table 2.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST BAKER CONDITIONS*

Cutterhead Type†	Depth of Cut Inches	Orientation of Grain in Machined Surface			
		Flat		Edge	
		Dry	Green	Dry	Green
2.....	1/32	0.62	0.76	1.06	1.07
	1/16	1.23	1.48	1.40	1.65
	3/32	1.50	2.13	1.76	2.21
	1/8	1.91	2.49	2.16	2.68
3.....	1/32	0.58	0.68	0.95	0.98
	1/16	1.04	1.24	1.21	1.55
	3/32	1.35	1.99	1.55	2.20
	1/8	1.58	2.52	1.78	2.43

*Refer to Table 1 for resume of fixed factors.

†2 is a flat face chipbreaker gib and 3 is a concave chipbreaker gib.

Table 3.—COMBINATIONS OF FACTORS UNDER TEST BAKER CONDITIONS THAT PRODUCED SATISFACTORY PLANED SURFACES*

Cutterhead Type	Depth of Cut Inches	Orientation of Grain in Machined Surface			
		Flat		Edge	
		Dry	Green	Dry	Green
2.....	1/32	---	*	*	*
	1/16	---	*	*	*
	3/32	---	---	*	*
	1/8	---	---	*	*
3.....	1/32	---	*	*	*
	1/16	---	*	*	*
	3/32	---	*	*	*
	1/8	---	*	*	*

*Asterisk indicates satisfactory surface.

completely unsatisfactory for another purpose.

D. Factors Investigated: The testing program was divided into a series of three experiments, two involving four variable factors, one involving three factors. To accomplish identity for the purpose of chart, photograph, and specimen labeling, as well as ease of discussion, each experiment was assigned a name from the phonetic alphabet, i.e., Baker, Charlie, Dog.

Factors investigated were:

Test Baker—cutterhead gib type, per cent moisture content, grain type, depth of cut.

Test Charlie—depth of cut, clearance angle, rake angle, per cent moisture content.

Test Dog—depth of cut, feed speed, number of jointed knives cutting.

Test Results and Discussion

A. Test Baker: This experiment was to test the interaction of the variables of cutterhead gib type, per cent moisture content, grain type, and depth of cut. A complete statement of factors involved is shown in Table 1.

The two cutterheads selected for this report were 8-knife, 9-inch nominal cutting-circle models. The cutter-

heads were identical except for gib shape. The two head types can be compared in Figs. 6A and 6B.

The dry specimens were run at the equilibrium moisture content reached in the laboratory—in this case 10.3 per cent. The green specimens were pressure treated in water for four days at approximately 65 psi to give an average moisture content of 100.7 per cent.

The stock was cut to obtain matched specimens of both flat and edge-grain lumber. All readings were made at approximately 300 FPM and at depths of cut of 1/32, 1/16, 3/32, and 1/8 inches.

The tabulation of horsepower requirements is shown in Table 2. Table 3 shows the combinations of factors that resulted in satisfactory surfaces. It was noted that the edge-grain stock provided 100 per cent satisfactory surfaces. The green flat-grain stock showed unsatisfactory surfaces only with heavy cuts using cutterhead two. By contrast, the dry flat-grain stock produced no satisfactory surfaces. The flat-grain stock suffered most from torn grain, although an unusually great amount of chip marking was also present on the dry flat-grain specimens. A study of the tabulation of horsepower requirements indicates the following:

1. All reported factors considered, the edge-grain stock required 15 per cent more power than did the flat-grain stock.

2. Cutterhead 2 required 11 per cent more power than cutterhead 3.

3. All reported factors considered, the green stock required 29 per cent more power than the dry stock.

4. Flat-grain green stock required 36 per cent more power than flat-grain dry stock. Edge-grain green stock required 25 per cent more power than edge-grain dry stock.

5. The difference in power demand between heads is doubly emphasized when considering dry stock as compared to green stock.

6. The difference in power demand between heads is approximately equal considering flat-grain stock compared to edge-grain stock.

7. Doubling the depth of cut results in something less than doubling the

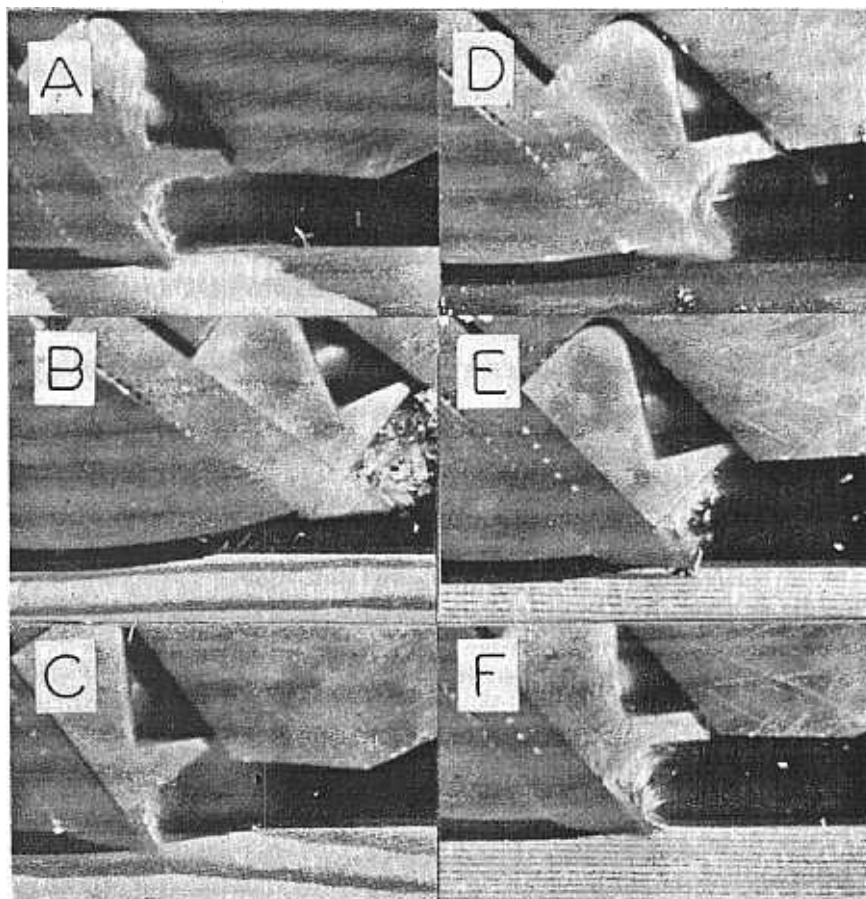


Fig. 6.—Test Baker. (A) Cutterhead type: No. 3; moisture content: dry; grain orientation in machined surface: edge; depth of cut: 0.125 inch. (B) Cutterhead type: No. 2; moisture content: dry; grain orientation in machined surface: edge; depth of cut: 0.0938 inch. (C) Cutterhead type: No. 2; moisture content: dry; grain orientation in machined surface: flat; depth of cut: 0.125 inch. (D) Cutterhead type: No. 3; moisture content: green; grain orientation in machined surface: edge; depth of cut: 0.0938 inch. (E) Cutterhead type: No. 2; moisture content: dry; grain orientation in machined surface: flat; depth of cut: 0.0625 inch. (F) Cutterhead type: No. 3; moisture content: dry; grain orientation in machined surface: flat; depth of cut: 0.0625 inch.

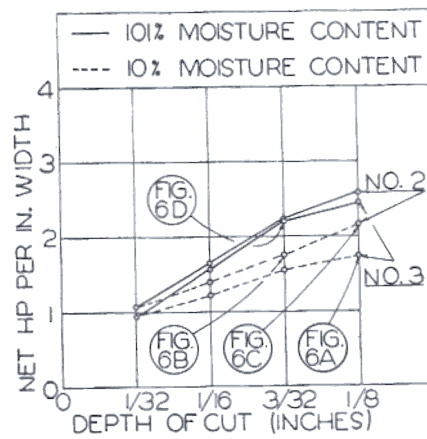


Fig. 7.—Net horsepower requirement for wood removal under Test Baker conditions comparing cutterheads 2 and 3 machining dry and green edge-grain stock.

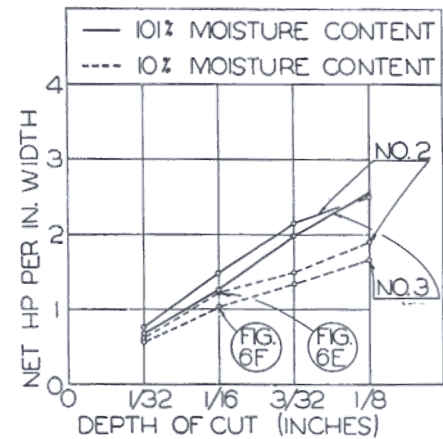


Fig. 8.—Net horsepower requirement for wood removal under Test Baker conditions comparing cutterheads 2 and 3 machining dry and green flat-grain stock.

Table 4.—RESUME OF FACTORS APPLYING TO TEST CHARLIE

Variable Factors:

Depth of Cut in Inches: 1/32, 1/16, 3/32, and 1/8
 Clearance Angle in Degrees: 5, 12½, 20, and 30
 Rake Angle in Degrees: —5, 0, 10, 20, 30, and 40
 Per Cent Moisture Content (based on O.D. weight):
 Green, i.e., 113.7 ±34
 Dry, i.e., 9.5 ±1

Fixed Factors:

Specimen:

General Description: A 20-foot long dry (approximately 10 percent M.C.) 1 by 12 was first ripped and then crosscut to yield eight 1 by 3's, each four feet nine inches long. Four of these were pressure treated in water at approximately 65 psi for seven days to simulate a green condition. One pair, i.e., one green piece and one dry piece, was utilized for each of the four clearance angle conditions.

Species: *Pseudotsuga taxifolia*

Wood Type: Heart

Rings per Inch: 20 ±5

Width of Machined Surface: Average 0.804 inches

Angle of Annual Rings to Machined Surface: 30 ±3 degrees

Spiral Grain: None

Specific Gravity:

Based on O.D. weight and green volume: 0.381 ±0.02

Based on O.D. weight and O.D. volume: 0.405 ±0.04

Inclination of Diagonal Grain to Direction of Feed: None

Cutterhead:

Head body: Jointer type, slotted for eight knives, slotted for 30-degree rake angle

Gibs: Concave face

Knives: 5/16-inch thick corrugated back, ground to appropriate angles

Number of Jointed Knives Cutting: 2

Cutting-circle Diameter in Inches: 9.05

Knife Extension beyond Gib: 0.312 inches

Width of Joint: 0.015 inches

Nominal RPM of Cutterhead: 3600

Feed Speed: 72.7 ±0.7 FPM

Table 5.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST CHARLIE CONDITIONS*

Rake Angle Deg.	Depth of Cut In.	Clearance Angle—Degrees							
		5		12½		20		30	
		Dry	Green	Dry	Green	Dry	Green	Dry	Green
-5	1/32	0.88	0.64	0.78	0.58	0.88	0.45	0.71	0.48
	1/16	1.33	0.99	1.24	0.95	1.33	0.77	1.22	0.75
	3/32	1.71	1.35	1.76	1.38	1.80	1.10	1.60	1.06
	1/8	2.15	1.50	2.10	1.45	2.20	1.44	1.97	1.37
0	1/32	0.72	0.59	0.64	0.50	0.67	0.49	0.65	0.39
	1/16	1.09	0.98	1.07	0.84	1.17	0.79	1.09	0.70
	3/32	1.42	1.40	1.39	1.19	1.51	1.05	1.50	0.98
	1/8	1.74	1.72	1.68	1.59	1.78	1.39	1.85	1.30
+10	1/32	0.88	0.54	0.86	0.36	0.88	0.34	0.41	0.40
	1/16	0.59	0.73	0.60	0.64	0.58	0.58	0.52	0.61
	3/32	0.79	1.13	0.80	0.87	0.82	0.85	0.91	0.90
	1/8	1.01	1.33	0.94	1.13	1.08	1.09	1.02	1.16
+20	1/32	0.26	0.30	0.28	0.30	0.25	0.29	0.24	0.25
	1/16	0.41	0.49	0.42	0.47	0.37	0.47	0.38	0.45
	3/32	0.54	0.71	0.56	0.67	0.49	0.65	0.48	0.69
	1/8	0.64	0.91	0.69	0.85	0.61	0.82	0.61	0.87
+30	1/32	0.18	0.22	0.18	0.22	0.15	0.17	0.17	0.19
	1/16	0.24	0.38	0.27	0.36	0.25	0.35	0.28	0.34
	3/32	0.33	0.44	0.36	0.51	0.31	0.46	0.33	0.47
	1/8	0.42	0.65	0.41	0.66	0.38	0.65	0.41	0.64
+40	1/32	0.15	0.18	0.15	0.17	0.13	0.17	0.14	0.18
	1/16	0.22	0.29	0.24	0.32	0.23	0.31	0.25	0.31
	3/32	0.29	0.40	0.31	0.40	0.29	0.41	0.32	0.41
	1/8	0.36	0.49	0.35	0.54	0.34	0.58	0.34	0.54

Test Baker the green moisture content was attained by pressure treating the relatively dry raw material in water at approximately 65 psi for seven days.

The test data sheet outlines the procedure of obtaining matched specimens. Table 5 tabulates the net horsepower requirements. Table 6 shows

the combinations of factors that resulted in satisfactory surfaces.

Of the rake angles considered, the 30-degree rake angle produced the most numerous satisfactory surfaces and was least sensitive to changes in clearance angle. Of the clearance angles considered, the 20-degree value

provided the highest percentage of satisfactory surfaces and was least sensitive to changes in rake angle. A 30-degree clearance angle was a close runner-up in this regard.

Fuzzy grain was much more prominent on green than on dry stock. Raised grain was more prominent on dry than on green stock. Only with the combinations of 20-degree clearance angle with 10, 20, 30, and 40-degree rake did the satisfactory green surfaces equal the number of satisfactory dry surfaces. With all other combinations a greater percentage of satisfactory dry surfaces was obtained.

At rake angles of plus 20 degrees and less, the controlling green defect was fuzzy grain. At the same rake angles the predominant dry defect was raised grain. At rake angles of 30 and 40 degrees, the predominant defect was torn grain for both green and dry stock. At a rake angle of 40 degrees in combination with clearance angles of 20 and 30 degrees, the dry stock suffered from a very considerable amount of chip marking.

A study of the horsepower requirements reveals the following relationships under Test Charlie conditions:

1. At rake angles of from plus 10 degrees to plus 40 degrees, and ignor-

Table 6.—COMBINATIONS OF FACTORS UNDER TEST CHARLIE CONDITIONS THAT PRODUCED SATISFACTORY PLANED SURFACES*

Rake Angle Deg.	Depth of Cut In.	Clearance Angle—Degrees							
		5		12½		20		30	
		Dry	Green	Dry	Green	Dry	Green	Dry	Green
-----	1/32	---	---	---	---	*	---	*	---
-----	1/16	---	---	---	---	*	---	*	---
-----	3/32	---	---	---	---	*	---	*	---
-----	1/8	---	---	---	---	*	---	*	---
0.....	1/32	*	*	---	---	---	---	*	*
-----	1/16	*	*	---	---	---	---	*	*
-----	3/32	*	*	---	---	---	---	*	*
-----	1/8	*	*	---	---	---	---	*	*
+20.....	1/32	*	*	---	---	---	---	*	*
-----	1/16	*	*	---	---	---	---	*	*
-----	3/32	*	*	---	---	---	---	*	*
-----	1/8	*	*	---	---	---	---	*	*
+30.....	1/32	*	*	---	---	---	---	*	*
-----	1/16	*	*	---	---	---	---	*	*
-----	3/32	*	*	---	---	---	---	*	*
-----	1/8	*	*	---	---	---	---	*	*
-----	1/32	---	---	---	---	---	---	*	---
-----	1/16	---	---	---	---	---	---	*	---
-----	3/32	---	---	---	---	---	---	*	---
-----	1/8	---	---	---	---	---	---	*	---

*Asterisk indicates satisfactory surface.

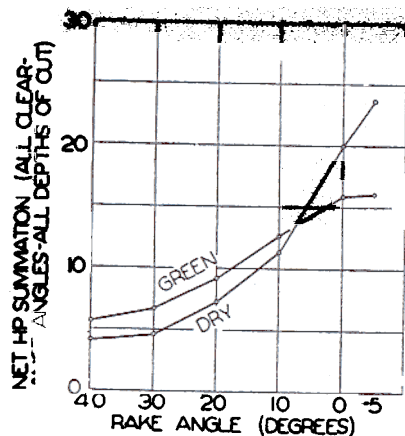


Fig. 9.—Relative net horsepower requirement for wood removal under Test Charlie conditions comparing dry and green stock at varying rake angles (ignoring factors of depth of cut and clearance angle).

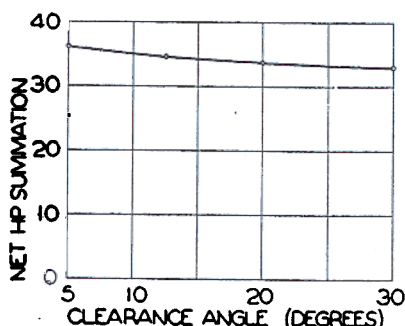


Fig. 10.—Relative net horsepower requirement for wood removal under Test Charlie conditions at varying clearance angles (ignoring factors of depth of cut, moisture content, and rake angle).

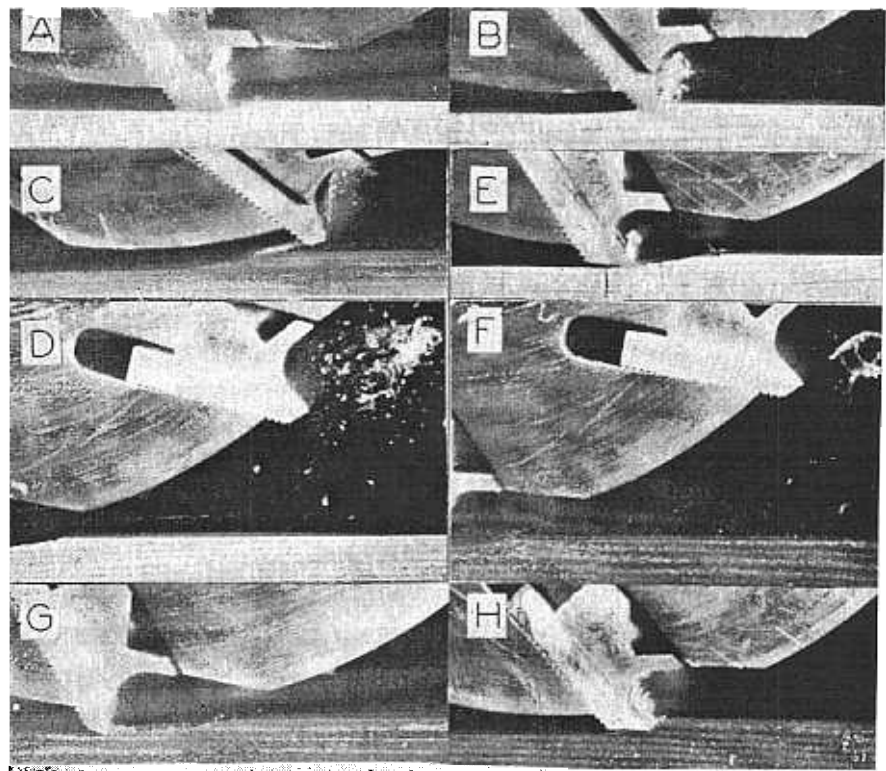


Fig. 11.—Test Charlie. (A) Rake angle: 30 degrees; clearance angle: 5 degrees; depth of cut: 3/32 inch; moisture content: dry. (B) Rake angle: -5 degrees; clearance angle: 5 degrees; depth of cut: 3/32 inch; moisture content: dry. (C) Rake angle: -5 degrees; clearance angle: 5 degrees; depth of cut: 3/32 inch; moisture content: green. (D) Rake angle: -5 degrees; clearance angle: 12½ degrees; depth of cut: 3/32 inch; moisture content: dry. (E) Rake angle: 30 degrees; clearance angle: 12½ degrees; depth of cut: 1/16 inch; moisture content: green. (F) Rake angle: -5 degrees; clearance angle: 12½ degrees; depth of cut: 1/16 inch; moisture content: green. (G) Rake angle: -5 degrees; clearance angle: 20 degrees; depth of cut: 3/32 inch; moisture content: green. (H) Rake angle: 40 degrees; clearance angle: 12½ degrees; depth of cut: 1/8 inch; moisture content: green.

ing the factors of depth of cut and clearance angle, green stock requires 19.2 per cent more power than dry stock.

2. At rake angles of zero degrees and minus 5 degrees, and ignoring the factors of depth of cut and clearance angle, green stock requires 26 per cent less power than dry stock.

3. Cutterhead power demand is markedly sensitive to rake angle, as is illustrated by Fig. 9, the power rising sharply as the rake angle decreases. A point of inflection is observed between 0 and 10 degrees of rake which applies to both green and dry stock.

4. Cutterhead power demand is not particularly sensitive to clearance angle. Fig. 10 represents a summation of Test Charlie data, consideration of factors other than clearance angle being omitted. This graph suggests a gradual decrease of cutterhead power demand with an increase in clearance angle.

A photographic review of the action reveals some phenomena of interest. In general the chips machined from green wood show more coherency than those machined from dry wood. For an example of this situation, refer to Figs. 11B and 11C, as well as Figs. 11D and 11F.

Two extremes in the manner of chip formation are discernible. Figs. 11B and 11G illustrate crushing parallel to the grain, whereas Fig. 11E illustrates intact chip formation through the mechanism of advance splitting. It will be noted that the advance splitting illustrated is at 30-degree rake, whereas the crushing parallel to the grain is at minus 5 degree rake. Figure 11H is an interesting view of a 40-degree rake angle in action.

The interference caused by low clearance angle is strikingly illustrated in Fig. 11A. This explains the presence of raised grain on dry specimens and fuzzy grain on green specimens when machined with a 5-degree clearance angle.

These photographs may offer an explanation for the interaction of moisture content and rake angle shown in Fig. 9. At high rake angles the chip removal is frequently by advance splitting, during which process strength in tension perpendicular to the grain plays an important part. At low rake angles where the chip is deformed by compression parallel to the grain, compressive strength parallel to the grain becomes a factor.

As the ratio of dry to green ultimate strength in tension perpendicular to the grain is approximately 1.24:1, and as the ratio of dry to green maximum crushing strength parallel to the grain is considered to be approximately 1.97:1 (10), the test results are consistent with the variation in the strength properties of wood.

Study of Fig. 9 shows that green specimens take significantly more power than do the dry specimens (when employing rake angles in the range of plus 10 to plus 40 degrees). Part of the explanation lies in the fact that the additional weight of the green chip, due to both its free and adsorbed water, increases the force necessary to accelerate it to cutterhead velocity. Other things being equal, this increase in force would be directly proportional to the increase in mass of the undeformed chip.

The change in velocity is considerable, inasmuch as in conventional or up-milling (which applies to this test) the stock, and with it the undeformed chip, is traveling in one direction at a speed of perhaps 500 FPM, whereas the knife which must pick up the deformed chip is traveling at approximately 8000 FPM in the opposite direction.

The transition from attached undeformed chip with a velocity of minus 500 FPM to unattached deformed chip with a velocity of plus 8000 FPM takes place within a distance of approximately one inch, the exact distance depending on cutterhead and feed conditions.

Thus the net horsepower curve for green stock is offset a positive amount on the ordinate. However, this fixed offset which makes green stock take more power than dry stock at high rake angles does not alter the shape of the curve, as the transition from wood failure in tension perpendicular to the grain to crushing parallel to the grain takes place with a decrease in rake angle.

From the point of view of horsepower consumption, it is of prime importance to note the significance of the chip inertia involved at cutterhead and feed speeds commonly used in industry. Tests recognizing the influence of this inertia can be expected to, and do, yield different results from

those revealed by Kivimaa (7) in his investigation, which involved the slow speed forming of chips with a radial chip testing device.

The explanation of decreased power requirement with increased clearance angle probably lies in the fact that interference, as illustrated in Fig. 11A, is eliminated with large clearance angles.

C. Test Dog: This experiment was a study of the interaction of the variables of number of jointed knives cutting, feed speed, and depth of cut. A complete statement of factors involved is shown in Table 7.

As subsequently explained, the test was limited to a maximum of approximately 600 FPM feed speed with 12 jointed knives cutting in a 9.44-inch cutting-circle. It would have been desirable to test an 11-inch diameter cutting-circle head fitted with 16 knives. With such a cutterhead a feed speed of 1000 FPM would be in order. If equipment of this capacity could have been used, confirmation of a suspected drastically increasing horsepower curve might have been detected at the higher feed speeds. However, inasmuch as the testing apparatus was limited in capacity, smaller cutterheads and slower feed speeds were employed.

A 12-knife, 9.44-inch cutting-circle diameter cutterhead was used in this test, and therefore the possibilities for numbers of knives in action was limited to 2, 4, 6, and 12. The excess knives were set back so that they would not engage the work. In order to maintain constant width of joint during the test, the knives were only jointed once prior to Test Dog and were not re-jointed during the progress of the test.

In the case of the 4-knife situation, which involved reseating knives 5 and 11 at the cutting-circle without subsequent rejoining, the resulting knife traces were something less than perfect. This situation probably accounts

Table 7.—RESUME OF FACTORS APPLYING TO TEST DOG

Variable Factors:

Depth of Cut in Inches: 1/64, 1/32, 1/16, 3/32, and 1/8
Nominal Feed Speed in FPM: 100, 300, 400, 500, and 600
Number of Jointed Knives Cutting: 2, 4, 6, and 12

Fixed Factors:

Specimen:

General Description: The test pieces consisted of four 20-foot long 1 by 3's ripped from a single dry (approximately 10 percent M.C.) 1 by 12 surfaced board. One of these pieces was randomly assigned to each of the four conditions calling for a different number of knives.

Species: *Pseudotsuga taxifolia*

Wood Type: Heart

Rings per Inch: 29 \pm 8

Width of Machined Surface: Average 0.776 inches

Angle of Annual Rings to Machined Surface: 44 \pm 4 degrees

Spiral Grain: Average value 1 1/2 inch per foot

Percent Moisture Content (based on O.D. weight): 7.33 \pm 0.5

Specific Gravity:

Based on O.D. weight and green volume: 0.393 \pm 0.04

Based on O.D. weight and O.D. volume: 0.445 \pm 0.06

Inclination of Diagonal Grain to Direction of Feed: None

Cutterhead:

Head Body: Joiner type, slotted for 12 knives

Gibs: Concave face

Knives: 3/16 inch thick with corrugated back

Cutting-Circle Diameter in Inches: 9.44

Rake: 27 1/2 degrees

Clearance: 22 1/2 degrees

Knife Extension beyond Gib: 0.25 inches

Width of Joint: 0.010 inches

Nominal RPM of Cutterhead: 3600

Table 8.—NET HORSEPOWER REQUIREMENT FOR WOOD REMOVAL FROM 1" WIDE STOCK UNDER TEST DOG CONDITIONS**

Depth of Cut in Inches	Number of Knives							
	12		6		4		2	
	Net HP	Feed Speed FPM	Net HP	Feed Speed FPM	Net HP	Feed Speed FPM	Net HP	Feed Speed FPM
1/64	1.24	600	0.78	611	0.84	612	0.75	608
1/32	1.85	598	1.55	605	1.62	608	1.11	602
1/16	2.84	585	2.45	596	2.59	602	3.01	594
3/32	3.85*	537	3.59	584	4.23*	571	4.04*	557
1/8	4.72*	537	4.36*	563	4.97*	547	4.53*	550
1/64	1.09	514	0.70	520	0.84	515	0.54	516
1/32	1.75	511	1.02	519	1.52	515	1.11	514
1/16	2.69*	494	2.41	516	2.47	509	2.04	510
3/32	3.30*	501	3.08*	509	3.19	510	3.66	507
1/8	4.21*	489	4.25*	506	4.69*	499	4.96*	497
1/64	0.97	416	0.61	419	0.66	418	0.52	422
1/32	1.56	414	1.04	417	1.15	416	0.93	421
1/16	2.30	414	1.59	417	2.07	414	1.84	417
3/32	2.89	408	2.41	416	2.89	415	2.80	415
1/8	3.49	404	3.16*	412	3.73	411	3.99*	408
1/64	1.02	307	0.47	312	0.41	308	0.36	308
1/32	1.39	306	0.79	310	0.90	308	0.70	308
1/16	2.15	302	1.19	309	1.38	306	1.26	308
3/32	2.58	304	1.79	309	2.04	307	2.13	307
1/8	2.97	323	2.29	307	2.63	305	2.76	305
1/64	0.77	108	0.35	108	0.31	109	0.19	108
1/32	1.04	108	0.47	108	0.42	109	0.27	108
1/16	1.48	108	0.74	108	0.66	109	0.36	108
3/32	1.75	108	0.92	108	0.84	109	0.64	108
1/8	2.08	108	1.09	108	1.00	109	0.80	108

*Wattmeter still rising at end of specimen run.
**Refer to Table 7 for resume of factors.

Table 9.—COMBINATIONS OF FACTORS UNDER TEST DOG CONDITIONS THAT PRODUCED SATISFACTORY PLANED SURFACES*

Feed Speed FPM	Depth of Cut in Inches	12	6	4	2
600	1/64	*	-	-	*
	1/32	*	-	-	*
	1/16	*	-	-	*
	3/32	*	-	-	*
	1/8	*	-	-	*
500	1/64	*	-	-	*
	1/32	*	-	-	*
	1/16	*	-	-	*
	3/32	*	-	-	*
	1/8	*	-	-	*
400	1/64	*	*	-	*
	1/32	*	*	-	*
	1/16	*	*	-	*
	3/32	*	*	-	*
	1/8	*	*	-	*
300	1/64	*	-	-	*
	1/32	*	-	-	*
	1/16	*	-	-	*
	3/32	*	*	-	*
	1/8	*	*	-	*
100	1/64	-	-	-	*
	1/32	-	-	-	*
	1/16	-	-	-	*
	3/32	-	-	-	*
	1/8	-	*	-	*

* Asterisk indicates satisfactory surface.

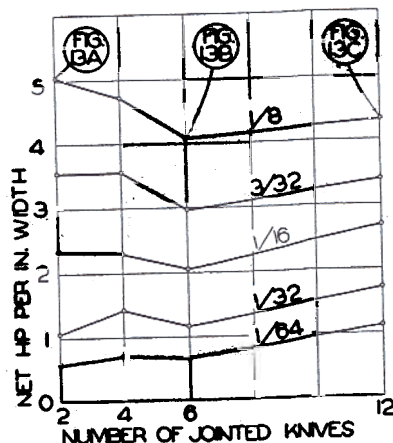


Fig. 12.—Net horsepower requirement for wood removal under Test Dog conditions comparing depth of cut of 1/64, 1/32, 1/16, 3/32, and 1/8 inch at 500 FPM feed speed with a varying number of knives.

for some of the discontinuity of the horsepower curves at the 4-knife values.

Depths of cut of 1/64, 1/32, 1/16, 3/32, and 1/8 inches were investigated. The feed speeds selected were in the range of 100, 300, 400, 500, and 600 FPM.

It will be observed that in the 500 FPM range, and more noticeably in the 600 FPM range, the limit of the testing equipment was reached, i.e., at the higher power demands the recording watt meter did not have time to reach a leveling off point. Furthermore, the feed motor RPM curve drooped considerably at the higher loads.

Recognizing the shortcomings of these tests, one can still gain a reasonably clear picture of the situation under different combinations of the variable factors involved.

A tabulation of the horsepower requirements is presented in Table 8. Table 9 shows the combination of factors that resulted in a satisfactory surface. It is apparent that high feed speeds with few knives have an adverse effect on the surface quality (in addition to that surface roughness created by the kinematics of the process). While one might suspect that deep cuts would contribute to surface defects, that trend is not particularly indicated by this tabulation. At feed speeds of 300 FPM and above, the controlling surface defect is torn grain. At 100 FPM the controlling factor is raised grain.

Study of the data shows that at low feed speeds the horsepower requirement of a cutterhead with a few knives is less than that of a cutterhead with many knives. However, at high feed

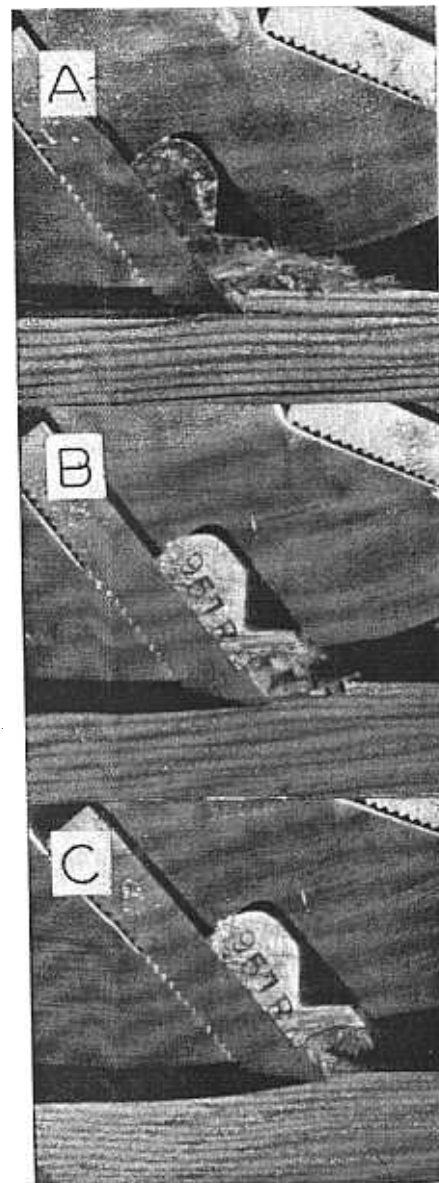


Fig. 13.—Test Dog. (A) Number of knives: 2; feed speed: 500 FPM; depth of cut: 0.125 inch. (B) Number of knives: 6; feed speed: 500 FPM; depth of cut: 0.125 inch. (C) Number of knives: 12; feed speed: 500 FPM; depth of cut: 0.125 inch.

speeds and medium to heavy cuts, the horsepower demand is relatively constant regardless of the number of knives. In fact, the slope of the curve may be reversed, with a few-knife cutterhead requiring more power at high speed than the cutterhead with many knives.

The explanation of this phenomenon (refer to Fig. 12) is illustrated in Fig. 13A, which shows a two-knife head at 1/8-inch depth of cut with a feed of 500 FPM. It is evident that the combination of deep advance splitting and restricted gullet space due to gib conformation creates a situation of high power requirement.

Compare the picture just described with that shown in Fig. 13B where a 6-knife head is also removing 1/8 inch at 500 FPM. Note that in this case the

considerably smaller chip is breaking against the gib in a reasonably orderly process, the result being that there is considerably less power demand. Fig. 13C illustrates somewhat the same situation.

The relationship of feed speed to power requirement for a given number of knives is shown in Fig. 14. A reasonably linear relationship between horsepower requirement and feed speed can be observed within the range of 100 to 300 FPM with heavier cuts, and 100 to 500 FPM with lighter cuts. A trend toward rapidly increasing slope is noted as the feed speed approaches 600 FPM. This phenomenon agrees with results reported by Kollmann (9).

The more recent findings of Caskey (3) indicate a lineal relationship between horsepower requirement and feed speed existing to approximately 450 FPM, after which point the slope of the curve begins to get steeper with increasing rapidity up to 900 FPM, beyond which point the tests did not extend.

From Fig. 14 it is evident that only at the heaviest cut, i.e., $1/8$ -inch, does the slope of the curve become such that the horsepower requirement doubles with a doubling speed. It will be noted that as more knives are added to the head this situation comes about at a higher speed.

Considering all combinations of numbers of knives and feed speeds, a linear relationship between depth of cut and net horsepower requirement can be observed. The curve is displaced above the X or horizontal axis so that if the depth of cut is doubled, the power requirement falls somewhat short of doubling.

The height of the Y intercept is proportional to the number of knives in the head, and the slope of the curve decreases as the number of knives in the head increases. In other words, in the feed speed range investigated the horsepower requirement for a two-knife cutterhead approximately doubles if the depth of cut is doubled. However, the horsepower requirement of a twelve-knife cutterhead falls considerably short of doubling when the depth of cut is doubled.

Conclusions

The various factors tested to determine their relationship to net cutterhead horsepower requirement have been discussed as they occurred in the individual tests of the series being reported. A cross comparison of the tests permits some conclusions to be drawn. The comments are grouped according to factor involved, the factors being arranged according to their association with cutterhead, feed, or workpiece.

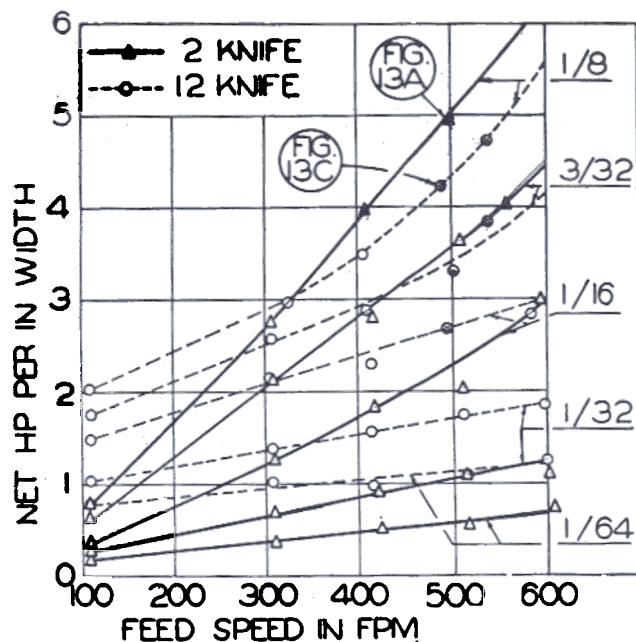


Fig. 14.—Net horsepower for wood removal under Test Dog conditions comparing 2- and 12-knife cutterheads at depths of cut of $1/64$, $1/32$, $1/16$, $3/32$, and $1/8$ inch at varying feed speeds. (Asterisk * indicates watt meter still rising at end of specimen run.)

Cutterhead Factors

A. Number of Knives (Test Dog): With low feed speeds and light cuts, the horsepower demand is approximately proportional to the number of jointed knives cutting, although in no case tested does a doubling of the number of knives cause a doubling of horsepower demand, other conditions remaining the same.

At a moderately deep cut, i.e., $1/16$ -inch, and at feed speeds that result in a feed per knife in excess of 0.25 inch, the number of knives employed makes little difference in horsepower demand when planing dry stock. (Note: Other tests, not reported here, show that with green stock a more marked proportionality exists between number of knives employed and horsepower demand at a particular feed speed.)

However, if one considers the relationship between horsepower requirement and number of knives in the special case where feed speed is varied to hold knife marks per inch constant, then a direct proportionality exists. In this situation, doubling the number of knives in a head will double the net horsepower demand.

B. Rake Angle (Test Charlie): A strong relationship exists between net cutterhead horsepower requirement and rake angle. Horsepower demand rises sharply with decreased rake angle, reaching a point of inflection somewhere between plus 15 and plus 5 degrees of rake angle, the slope of the curve thereafter decreasing for smaller rake angles. This holds true whether the stock is green or dry. The rise in horsepower demand with a decrease

in rake angle when machining green stock is not as pronounced as when machining dry stock.

When machining dry stock, a rake angle of 15 degrees requires half as much power as does a 0-degree rake angle, and twice as much power as does a 30-degree rake angle.

C. Clearance Angle (Test Charlie): The tests indicate that the net cutterhead horsepower requirement is inversely related to clearance angle. The trend is not pronounced, however, as a 5-degree clearance angle requires only 9 per cent more power than a 30-degree clearance angle (all test factors considered).

The practical limitations on clearance angle therefore govern its magnitude. For example, a clearance angle of 30 degrees in combination with a rake angle of 40 degrees results in an edge that is too fragile for most planing purposes. On the other hand, a 5 degree clearance angle results in an undesirable width of heel after even the lightest of jointing operation.

D. Cutterhead Type (Test Baker, Test Dog): These comments are restricted to conclusions drawn from the gib types tested. The photographs disclose, and the power readings confirm, that the most desirable gib type should present ample gullet space for the feeds and speeds contemplated.

Further, the cutterhead should be designed to eliminate any interference with the chip as it leaves the gullet space. Ideally, the gib face should be concave with the curve of the gib face being in as near tangential relationship to the knife face as possible.

Of the gibs tested, the model designed with no face curvature required 11 per cent more power than the model with a concave face, both cutterheads involved having 30-degree rake knives and approximately 0.3-inch knife extension. On green stock the difference was more pronounced, and on dry stock less pronounced.

Feed Factors

A. Feed Speed (Test Dog): With relatively heavy cuts, i.e., 1/16 to 1/8 inches, an approximately linear relationship exists between horsepower requirement and feed speed within the range 100–300 FPM. This range of linearity is extended to 100–500 FPM for lighter cuts.

There is a trend toward rapidly increasing horsepower demand as the feed speed approaches and exceeds 600 FPM. The rate of horsepower increase in this upper feed speed range is accelerated with many-knife heads as compared to heads mounting few knives.

Only with heavy cuts on the order of 1/8-inch deep does the slope of the curve become such that the horsepower requirement doubles with a doubling of feed speed. As more knives are added to the head this degree of slope comes about in a higher speed range. With smaller depths of cut a doubling of feed rate does not result in a doubling of horsepower requirement.

B. Depth of Cut (Tests Baker, Charlie, and Dog): A somewhat linear relationship between net cutterhead horsepower demand and depths of cut of 1/16 inch and greater can be observed, although the heavier cuts are in general more efficient than the lighter cuts. The curve is displaced above the X or horizontal axis so that as the depth of cut is doubled the power requirement falls short of doubling.

The height of the Y intercept is related to the number of knives in the head and the slope of the curve decreases as the number of knives increases. In other words, at a given feed speed (in the range 100–600 FPM) the horsepower requirement for a 2-knife cutterhead approximately doubles as the depth of cut is doubled. However, the horsepower requirement of a 12-knife cutterhead falls considerably short of doubling when the depth of cut is doubled.

Below 1/16-inch depth of cut, the curve bends toward 0 horsepower demand as the depth of cut approaches

0. Because of the many interactions involved, a generalization is very difficult to make concerning depth of cut as an isolated factor affecting net cutterhead horsepower demand.

Workpiece Factors

A. Grain Type (Test Baker): In comparing edge-grain specimens to flat-grain specimens in the portion of the tests reported, edge-grain stock requires 15 per cent more power than flat-grain stock. This difference in power requirement is sensitive to moisture content, green edge-grain stock requiring only 11 per cent more power than green flat-grain stock, compared to dry edge-grain stock which requires 20 per cent more power than dry flat-grain stock. Decreased rake angles emphasize the greater power demand of the edge-grain stock over flat-grain stock.

B. Moisture Content (Tests Baker and Charlie): At rake angles of from plus 10 to plus 40 degrees, green stock takes significantly more power than dry stock. In this rake angle range, and at the moisture contents tested, green specimens take approximately 20 per cent more power than dry specimens. In this rake angle range the difference between the power demand of green and dry stock is emphasized with flat-grain stock and minimized with edge-grain stock. Under Test Charlie conditions and at rake angles of 0 degrees and minus 5 degrees, green stock requires approximately 26 per cent less power than dry stock.

Space has not permitted the discussion of other factors tested (8), including specific gravity of stock, direction of cutterhead rotation with relation to direction of feed, angle between rotational axis of cutterhead and direction of feed, knife extension, width of joint, and diameter of cutting circle. A report on the effect of these variables on cutterhead power requirement will be published at a later date.

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Discussion

R. P. Hotelling (Henry Disston and Sons): Did you observe any decrease of clearance because the knife crushed the wood?

Mr. Koch: No. The photos are stills so we couldn't observe compression of wood. None was indicated, however.

L. A. Patonsky (Wabash Screen Door Co.): How much of the power consumed in machining wood is used for severing fibers and how much for removing chips?

Mr. Koch: I made some calculations concerning the inertia forces involved in removing dry and wet chips (diagram) and conclude that the power involved in carrying away the chip (as differentiated from severing the fibers) is of considerable significance.

Rex Reynolds (Kennametal, Inc.): Have you tried carbide with this test?

Mr. Koch: Not with this test, as we needed easily jointed knives.

Mr. Reynolds: Did you retain the setup so you could run tests with carbide?

Mr. Koch: No but it is reproducible.